

On probing Higgs couplings in $H \rightarrow ZV$ decays

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We analyze the possibility of probing Higgs couplings in the rare decays $H \rightarrow ZV$, V being a vector quarkonium state. These rare decays involve both gauge as well as the Yukawa sectors and either of them can be potentially anomalous. Moreover, as both V and Z can decay into pair of charged leptons, they provide experimentally clean channels and future LHC runs should observe such decays. We discuss origin of all possible contributions and their relative strengths in $H \rightarrow ZV$ process. We perform a model independent analysis and show how angular asymmetries can be used for probing Higgs couplings in the rare decays, taking further decays of V and Z to pair of leptons into account. The angular asymmetries can play a significant role in probing Higgs couplings to SM particles in both gauge and Yukawa sectors.

I. INTRODUCTION

The ATLAS and CMS collaborations at Large Hadron Collider (LHC) have recently discovered a new bosonic resonance of mass around 125 GeV [1–5]. Measuring its coupling to different Standard Model (SM) particles and establishing its nature are going to be leading aims of future LHC runs. Although it is yet to be confirmed as SM Higgs, in this paper we specify this resonance as Higgs and denote it by H . Any deviations from its SM nature should exhibit in its coupling to different particles. Anomalous couplings of Higgs may come in both gauge and Yukawa sectors. Establishing the nature of the Higgs will require a precise measurement of its gauge as well as Yukawa couplings. In future LHC runs the coupling of Higgs to W, Z bosons will be measured in several different channels such as $H \rightarrow ZZ^* \rightarrow 4\ell$. However, measuring its coupling to fermions as well as loop induced couplings like $HZ\gamma$ are going to be relatively more challenging.

In this regard, several studies [6–27] have been directed towards rare Higgs decays such as $H \rightarrow ZV$; V being a vector quarkonium ($J^{PC} = 1^{--}$). Although the branching ratios are small, rare Higgs decays offer complementary information about Higgs couplings [7] and can serve as important probe of “New Physics” (NP). Besides, subsequent decays of Z and V into pair of leptons make them experimentally clean channels. Moreover, the decay rates are further enhanced by resonant production of V and could be seen in high luminosity LHC runs or in future colliders. Among rare Higgs decays, the decay to a vector quarkonium ($J/\psi, \Upsilon$) received considerable attention in recent times. Refs. [8–10] have studied $H \rightarrow ZV$ process with the aim to probe Higgs couplings and new physics.

There exist three different processes that contribute to the $H \rightarrow ZV$ decay. Refs. [7, 8] calculate the decay rates for $H \rightarrow ZV$ via $H \rightarrow Z^*Z$ with $Z^* \rightarrow V$. Although in SM the process $H \rightarrow Z\gamma^* \rightarrow ZV$ is loop suppressed, Ref. [10] shows that it can provide a significant contribution depending on the nature of the vector boson V .

There exist a third contribution where $H \rightarrow ZV$ is produced via $H \rightarrow q\bar{q} \rightarrow ZV$ and Ref. [9] studies this channel assuming anomalous coupling in Yukawa sector. As any of the above three processes could be anomalous, in this paper we perform a model independent analysis of $H \rightarrow ZV$ decay without making any assumption on its origin.

We first calculate the SM contribution of the three processes and their respective interferences to the $H \rightarrow ZV$ decay. We also write down the most general $HZZV$ vertex and derive corresponding angular asymmetries from it. These asymmetries have been discussed in Ref. [28, 29] in the context of $H \rightarrow ZZ^* \rightarrow 4\ell$ and also in Ref. [13] to probe non standard Higgs coupling via angular analysis. They provide powerful tools which can probe SM as well as any anomalous contributions to the decay. Similar asymmetry has also been discussed in Ref. [9] to measure CP odd properties of Yukawa sector in $H \rightarrow ZV$ decays. In our work we construct all possible asymmetries and perform a case by case analysis discussing relative contributions of different diagrams and their consequences on respective asymmetries.

The plan of the paper goes as follows. In section II we compute the SM contributions of the three processes and compare their relative strengths. Section III is devoted to formalize the angular analysis and construction of angular asymmetries for $H \rightarrow ZV$ with further decays of V and Z into pair of leptons. We also discuss how to probe different Higgs coupling using these angular asymmetries. In Section IV we conclude our results.

II. STANDARD MODEL CONTRIBUTION OF DIFFERENT CHANNELS TO $H \rightarrow ZV$ PROCESS

We start our discussion by first estimating the relative strength of SM contribution of different channels to the process $H \rightarrow ZV$, where V is a vector quarkonium ($J^{PC} = 1^{--}$). In particular we will focus on $J/\psi(1S)$ and $\Upsilon(1S)$ but our analysis is general and can be used for any vector quarkonium. These decays receive contributions from three different diagrams as shown in Fig.1. Some of these contributions have been individually stud-

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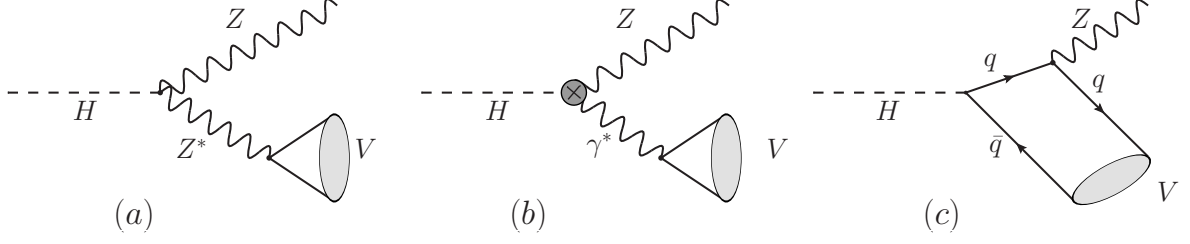


FIG. 1. Feynman diagrams contributing to $H \rightarrow ZV$, V being a vector quarkonium resonance. The diagrams originate from three different couplings: (a) tree level HZZ coupling, (b) loop induced $HZ\gamma$ coupling, (c) $Hq\bar{q}$ Yukawa coupling.

ied in previous works [8–10] but a combined analysis is still lacking.

The relative strengths of the diagrams and their interference terms vary depending on the final vector quarkonium resonance. Because of quite different masses of J/ψ and Υ resonances the relative strengths of these diagrams differ appreciably in the two cases. We explicitly calculate the individual contributions for $J/\psi(1S)$ and $\Upsilon(1S)$ to demonstrate this fact.

In SM the first diagram Fig.1(a), originates from tree level HZZ gauge coupling. The matrix element for it is given by

$$\mathcal{M}_1 = -\mathcal{K}_1 (a_1^{ZZ} g_{\mu\nu}) \epsilon_1^{*\mu} \epsilon_2^{*\nu} \quad (1)$$

where

$$\mathcal{K}_1 = \frac{2g g_V^q f_V}{\cos \theta_W} \frac{M_V M_Z^2}{M_Z^2 - M_V^2}, \quad (2)$$

with θ_W as Weinberg angle, $g_V^q = (\frac{1}{4} - \frac{2}{3} \sin^2 \theta_W)$ for Charm(c) quark and $g_V^q = (-\frac{1}{4} + \frac{1}{3} \sin^2 \theta_W)$ for Bottom(b) quark. Also, $\epsilon_1^\mu(q_1)$ and $\epsilon_2^\nu(q_2)$ are the polarization vectors for Z and V having momenta q_1 and q_2 respectively. Moreover, f_V is defined by the matrix element $\langle 0 | \bar{q} \gamma^\mu q | V(q_2, \epsilon_2) \rangle = f_V M_V \epsilon_2^\mu$.

Since in SM the $HZ\gamma$ coupling is forbidden at tree level, the second diagram Fig.1(b), can only arise via loop processes. One can compute this process by writing down an effective lagrangian for the $HZ\gamma$ coupling [10–12, 30] The matrix element for this diagram is given by

$$\mathcal{M}_2 = -\mathcal{K}_2 (a_1^{Z\gamma} q_1 \cdot q_2 g_{\mu\nu} - a_2^{Z\gamma} q_{1\nu} q_{2\mu}) \epsilon_1^{*\mu} \epsilon_2^{*\nu} \quad (3)$$

where

$$\mathcal{K}_2 = \frac{g \alpha Q^f f_V}{2\pi v} \frac{C_{Z\gamma}}{M_V}. \quad (4)$$

$C_{Z\gamma}$ is the dimensionless effective coupling constant for the $HZ\gamma$ vertex [11, 12, 30], $\alpha = \frac{e^2}{4\pi}$ and $Q^f = \frac{2}{3}, \frac{-1}{3}$ for $V = J/\psi, \Upsilon$ respectively.

The third contribution Fig.1(c) comes from $Hq\bar{q}$ Yukawa coupling and is given by

$$\mathcal{M}_3 = -\mathcal{K}_3 (a_1^{Zq\bar{q}} q_1 \cdot q_2 g_{\mu\nu} - a_2^{Zq\bar{q}} q_{2\mu} q_{1\nu}) \epsilon_1^{*\mu} \epsilon_2^{*\nu} \quad (5)$$

where

$$\mathcal{K}_3 = \frac{4\sqrt{3} g g_V^q \phi_0}{\cos \theta_W (M_H^2 - M_Z^2 - M_V^2)} \left(\frac{M_V G_F}{2\sqrt{2}} \right)^{\frac{1}{2}}, \quad (6)$$

and ϕ_0 is the wave function of the vector quarkonium resonance evaluated at zero three momentum [15, 31, 32].

The total decay width for $H \rightarrow ZV$ process is combination of all three contributions given by

$$\Gamma_{total} = \Gamma_1 + \Gamma_2 + \Gamma_3 + \Gamma_{12} + \Gamma_{13} + \Gamma_{23}. \quad (7)$$

where Γ_i are obtained from $|\mathcal{M}_i|^2$ and Γ_{ij} are interference terms between \mathcal{M}_i and \mathcal{M}_j with $i, j = 1, 2, 3$. The individual contributions for both $J/\psi(1S)$ and $\Upsilon(1S)$ are listed in Table I.

TABLE I. Contributions to the branching fraction from the three contributing diagrams and their interferences for $J/\psi(1S)$ and $\Upsilon(1S)$ resonances. The total decay width of Higgs is assumed to be 4.07 MeV. Values of $f_V = 0.405(0.680)$ GeV [8] and $\phi_0^2 = 0.073(0.512)$ GeV³ [32] for $J/\psi(\Upsilon)$.

$\mathcal{B}r(H \rightarrow ZV)$	$J/\psi(1S)$	$\Upsilon(1S)$
$\mathcal{B}r_{\Gamma_1}$	1.75×10^{-6}	1.68×10^{-5}
$\mathcal{B}r_{\Gamma_2}$	1.14×10^{-6}	8.33×10^{-8}
$\mathcal{B}r_{\Gamma_3}$	8.52×10^{-9}	5.80×10^{-7}
$\mathcal{B}r_{\Gamma_{12}}$	4.50×10^{-7}	1.10×10^{-6}
$\mathcal{B}r_{\Gamma_{13}}$	3.89×10^{-8}	2.89×10^{-6}
$\mathcal{B}r_{\Gamma_{23}}$	1.97×10^{-7}	4.40×10^{-7}

From Table I it is clear that the relative contributions of the three channels is different for J/ψ and Υ resonances. In case of J/ψ the dominant contributions come from Γ_1 and Γ_2 corresponding to HZZ and $HZ\gamma$ couplings respectively. The subleading contributions come from the interference terms Γ_{12} and Γ_{23} . The contribution Γ_3 coming from $Hq\bar{q}$ coupling is negligibly small. The major contribution from Yukawa sector will come from the interference term Γ_{23} . Therefore while probing the anomalous Yukawa couplings one should not neglect the contribution of the interference terms over Γ_3 .

However, in case of Υ the situation is quite different. The leading contribution comes only from the Γ_1 term whereas Γ_{12} and Γ_{13} provide the subleading contributions. The contribution of Γ_3 is now larger than Γ_2 but still negligibly small compared to Γ_1 . Again as before

while probing anomalous Yukawa coupling the effect of interference terms can not be neglected.

As discussed above the rare Higgs decays $H \rightarrow ZV$ are sensitive not only to HZZ coupling but also to $HZ\gamma$ and $Hq\bar{q}$ couplings. Moreover, depending on nature of V , the contribution of various Higgs couplings to the decay widths vary widely. Hence these decay modes have potential to provide information complimentary to $H \rightarrow ZZ^* \rightarrow 4\ell$ “golden channel”. Also, $H \rightarrow ZV$ decays followed by a subsequent decay of Z and V into pair of leptons will provide a experimentally clean channel that can be used to probe them in future colliders or high luminosity LHC runs. In next section we will discuss the angular analysis technique which provide a powerful tool for probing such couplings.

III. ANGULAR ANALYSIS AND OBSERVABLES FOR $H \rightarrow ZV \rightarrow 4\ell$ PROCESS

In this section we formalize the necessary technique to probe HZV vertex. We start with writing down general structure of the vertex and the different helicity amplitudes for $H \rightarrow ZV$ process. The general Lorentz structure of the HZV vertex can be written as

$$V_{HZV}^{\alpha\beta} = \left(a_1 g^{\alpha\beta} + a_2 P^\alpha P^\beta + i a_3 \epsilon^{\alpha\beta\mu\nu} q_{1\mu} q_{2\nu} \right), \quad (8)$$

where a_1 , a_2 and a_3 are vertex factors, P is the momentum of Higgs boson and q_1 and q_2 are momenta of Z and V respectively. In SM

$$a_1^{\text{SM}} = -(\mathcal{K}_1 a_1^{ZZ} + \mathcal{K}_2 a_1^{Z\gamma} q_{1 \cdot q_2} + \mathcal{K}_3 a_1^{q\bar{q}} q_{1 \cdot q_2}), \quad (9)$$

$$a_2^{\text{SM}} = \left(\mathcal{K}_2 a_2^{Z\gamma} + \mathcal{K}_3 a_2^{q\bar{q}} \right), \quad (10)$$

$$a_3^{\text{SM}} = 0. \quad (11)$$

The couplings a_1 , a_2 and a_3 can be extracted via angular asymmetries discussed below. Any deviation from SM values will indicate anomalous nature of $H \rightarrow ZV$ decay.

The decay under consideration can be expressed in terms of three helicity amplitudes \mathcal{A}_L , \mathcal{A}_\parallel and \mathcal{A}_\perp defined in the transversity basis as

$$\mathcal{A}_L = (M_H^2 - M_Z^2 - M_V^2) a_1 + M_H^2 X^2 a_2, \quad (12)$$

$$\mathcal{A}_\parallel = \sqrt{2} M_H M_V a_1, \quad (13)$$

$$\mathcal{A}_\perp = \sqrt{2} M_H^2 M_V X a_3, \quad (14)$$

where M_H , M_Z and M_V are masses of H , Z and V respectively with

$$X = \frac{\sqrt{\lambda(M_H^2, M_Z^2, M_V^2)}}{2M_H} \quad (15)$$

where $\lambda(x, y, z) = x^2 + y^2 + z^2 - 2xy - 2xz - 2yz$. The helicity amplitudes \mathcal{A}_L , \mathcal{A}_\parallel and \mathcal{A}_\perp have definite parity properties. \mathcal{A}_L , \mathcal{A}_\parallel are CP even in nature where as \mathcal{A}_\perp is CP odd.

The full angular distribution for $H \rightarrow Z_{(\ell^+\ell^-)} V_{(\ell^+\ell^-)}$ is given by following expression

$$\begin{aligned} \frac{8\pi}{\Gamma} \frac{d^3\Gamma}{d\cos\theta_1 d\cos\theta_2 d\phi} &= 1 + \frac{|f_\parallel|^2 - |f_\perp|^2}{4} \cos 2\phi (1 - P_2(\cos\theta_1))(1 - P_2(\cos\theta_2)) + \frac{1}{2} \text{Im}(f_\parallel f_\perp^*) \sin 2\phi \\ &\times (1 - P_2(\cos\theta_1))(1 - P_2(\cos\theta_2)) + \frac{1}{2} (1 - 3|f_L|^2) (P_2(\cos\theta_1) + P_2(\cos\theta_2)) + \frac{1}{4} (1 + 3|f_L|^2) P_2(\cos\theta_1) P_2(\cos\theta_2) \\ &+ \frac{9}{8\sqrt{2}} \left(\text{Re}(f_L f_\parallel^*) \cos\phi + \text{Im}(f_L f_\perp^*) \sin\phi \right) \sin 2\theta_1 \sin 2\theta_2 + \eta \left(\frac{3}{2} \text{Re}(f_\parallel f_\perp^*) (\cos\theta_2 (2 + P_2(\cos\theta_1)) \right. \\ &\left. - \cos\theta_1 (2 + P_2(\cos\theta_2))) - \frac{9}{2\sqrt{2}} \text{Re}(f_L f_\perp^*) \cos\theta_2 \cos\phi \sin\theta_1 \sin\theta_2 + \frac{9}{2\sqrt{2}} \text{Im}(f_L f_\parallel^*) \cos\theta_2 \sin\phi \sin\theta_1 \sin\theta_2 \right), \end{aligned} \quad (16)$$

where the angle $\theta_1(\theta_2)$ is the angle between three momenta of ℓ^+ in $Z(V)$ rest frame and the direction of three momenta of $Z(V)$ in H rest frame. The angle ϕ is defined as the angle between the normals to the planes defined by $Z \rightarrow \ell^+\ell^-$ and $V \rightarrow \ell^+\ell^-$ in H rest frame. The expressions for *helicity fractions* f_L , f_\parallel and f_\perp are given in the appendix.

Integrating Eq.(16) with respect to the angles $\cos\theta_1$ or

$\cos\theta_2$ or ϕ , one can obtain following uniaxial distributions:

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta_1} = \frac{1}{2} + t_2 P_2(\cos\theta_1) - t_1 \cos\theta_1, \quad (17)$$

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta_2} = \frac{1}{2} + t_2 P_2(\cos\theta_2), \quad (18)$$

$$\frac{2\pi}{\Gamma} \frac{d\Gamma}{d\phi} = 1 + u_2 \cos 2\phi + v_2 \sin 2\phi \quad (19)$$

where $P_2(\cos \theta_{1,2})$ are second degree Legendre Polynomial and

$$t_1 = \frac{3}{2} \eta \text{Re}(f_{\parallel} f_{\perp}^*), \quad (20)$$

$$t_2 = \frac{1}{4} (1 - 3|f_L|^2), \quad (21)$$

$$v_2 = \frac{1}{2} \text{Im}(f_{\parallel} f_{\perp}^*), \quad (22)$$

$$u_2 = \frac{1}{4} (|f_{\parallel}|^2 - |f_{\perp}|^2). \quad (23)$$

The uniangular distributions in Eq.(17), Eq.(18) and Eq.(19) will give us arsenal to probe the $H \rightarrow ZV$ coupling. The observables t_1 , t_2 , u_2 and v_2 can be extracted using following asymmetries:

$$t_1 = \frac{1}{\Gamma} \left(\int_{-1}^0 - \int_0^{+1} \right) \frac{d\Gamma}{d \cos \theta_1} d \cos \theta_1, \quad (24)$$

$$t_2 = \frac{4}{3\Gamma} \left(\int_{-1}^{-\frac{1}{2}} - \int_{-\frac{1}{2}}^{+\frac{1}{2}} + \int_{+\frac{1}{2}}^{+1} \right) \frac{d\Gamma}{d \cos \theta_{1,2}} d \cos \theta_{1,2} \quad (25)$$

$$v_2 = \frac{\pi}{2\Gamma} \left(\int_{-\pi}^{-\frac{\pi}{2}} - \int_{-\frac{\pi}{2}}^0 + \int_0^{+\frac{\pi}{2}} - \int_{+\frac{\pi}{2}}^{+\pi} \right) \frac{d\Gamma}{d\phi} d\phi, \quad (26)$$

$$u_2 = \frac{\pi}{2\Gamma} \left(\int_{-\pi}^{-\frac{3\pi}{4}} - \int_{-\frac{3\pi}{4}}^{-\frac{\pi}{4}} + \int_{-\frac{\pi}{4}}^{\frac{\pi}{4}} - \int_{\frac{\pi}{4}}^{\frac{3\pi}{4}} + \int_{\frac{3\pi}{4}}^{\pi} \right) \frac{d\Gamma}{d\phi} d\phi. \quad (27)$$

The observables t_1 , t_2 , u_2 , v_2 are functions of a_1 , a_2 , a_3 and their measurements will allow us to probe $H \rightarrow ZV$ coupling. In SM t_1 , t_2 , u_2 , v_2 have unique values which can be computed using the SM values of the couplings a_1 , a_2 , a_3 given in Eq.(9), Eq.(10) and Eq.(11). The anomalous nature, if any, of a_1 , a_2 , a_3 will show up in the observables as deviation from their SM values.

As discussed in Section II, the rare Higgs decays are sensitive to HZZ , $HZ\gamma$ and $Hq\bar{q}$ couplings. Therefore, any deviation of the observables t_1 , t_2 , u_2 , v_2 from their SM values can not a priori be attributed to anomalous nature of any one sector. However, when taken in conjugation with other decays like $H \rightarrow ZZ^* \rightarrow 4\ell$ they can provide complimentary information about $HZ\gamma$ and $Hq\bar{q}$ couplings. For example, if any hint of anomalous nature is found in $H \rightarrow ZZ^* \rightarrow 4\ell$ decay, one expects to see corresponding deviations in the observables of $H \rightarrow ZV$ for both J/ψ and Υ . On the other hand if $H \rightarrow ZZ^* \rightarrow 4\ell$ decay observables turn out to be consistent with the SM values then HZZ contribution in rare decays should also be SM like. In such a scenario any observed anomaly in $H \rightarrow ZV$ can only come from either $HZ\gamma$ or $Hq\bar{q}$ couplings. As the magnitude of their contributions in

$H \rightarrow J/\psi$ and $H \rightarrow \Upsilon$ are quite different, this fact can be exploited to further narrow down the origin of the anomalous behaviour. Moreover, for Higgs decay to both J/ψ and Υ , the effect of any anomaly in Yukawa sector will manifest itself predominantly through the interference terms.

In principle Higgs can have anomalous couplings in more than one sector. If so, it will be relatively more difficult to make any definite conclusions about the relative contributions of the three sectors to the anomalous couplings of Higgs in $H \rightarrow ZV$ decays.

IV. CONCLUSION

We discuss the feasibility of probing the rare Higgs decays $H \rightarrow ZV$ followed by further decay of V and Z into pair of leptons. We have shown that the $H \rightarrow ZV$ decays receive contributions from gauge as well as Yukawa sector and depending on the nature of V , can be sensitive to anomalous couplings in more than one sector. They can provide complimentary information about the gauge and Yukawa couplings of Higgs. We then showed how observables extracted as angular asymmetries will allow us to extract information about HZV coupling. Such asymmetries have the potential to infer the nature of gauge and Yukawa couplings of Higgs in future colliders or high luminosity LHC runs.

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Appendix A

Helicity fractions f_L , f_{\parallel} and f_{\perp} are defined as

$$f_{\lambda} = \frac{\mathcal{A}_{\lambda}}{\sqrt{|\mathcal{A}_L|^2 + |\mathcal{A}_{\parallel}|^2 + |\mathcal{A}_{\perp}|^2}}, \quad (A1)$$

where $\lambda \in \{L, \parallel, \perp\}$ and

$$\Gamma = \mathcal{N} \left(|\mathcal{A}_L|^2 + |\mathcal{A}_{\parallel}|^2 + |\mathcal{A}_{\perp}|^2 \right), \quad (A2)$$

with

$$\mathcal{N} = \frac{1}{2^7} \frac{1}{9\pi^3} \frac{X}{M_H^2} \frac{\mathcal{K}^2}{\Gamma_Z M_Z \Gamma_V M_V} a_v^2 (v_{\ell}^2 + a_{\ell}^2) \quad (A3)$$

$v_{\ell} = 2I_{3\ell} - 4e_{\ell} \sin^2 \theta_W$, $a_{\ell} = 2I_{3\ell}$, $a_v = \frac{4\pi Q^f \alpha f_V}{\sqrt{3} M_V}$ and η is defined as $\eta = \frac{2v_{\ell} a_{\ell}}{v_{\ell}^2 + a_{\ell}^2}$.

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